CROP ECOLOGY, MANAGEMENT & QUALITY

Crop Yield and Nitrogen Accumulation Response to Tillage of a Coastal Plain Soil

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ABSTRACT

Delineation of the benefit derived from either surface or subsoil tillage is important for the advancement of soil-conserving crop production systems in the Coastal Plain. The objective of this experiment was to measure the impact of surface and subsoil tillage of a sandy Coastal Plain soil (fine-loamy, siliceous, thermic Typic Kandiudult) on grain yield and nitrogen accumulation for a 2-yr rotation of corn (*Zea mays*) and wheat–double-cropped soybean {(*Triticum aestivum* L.) and [*Glycine max* (L.) Merr.]}. Soils of the experimental plots initially possessed different surface residue and organic matter characteristics because they had received in-row subsoiling with either surface-disking tillage or no surface tillage for the previous 18-consecutive years. The current experiment was conducted from 1997 to 2001, which was an exceptionally dry period. Thus, results of this experiment provide insight into how these cropping and tillage treatments performed during one of the driest 5-yr periods of the last half century. In each year, both phases of the crop rotation were grown in plots with the following tillage treatments: (i) neither surface nor subsoil tillage, (ii) paratill subsoiling without surface tillage, (iii) surface tillage without subsoiling, and (iv) both surface tillage and paratill subsoiling. Soybean was not significantly affected by any tillage treatment. With subsoiling, corn grain yields (4-yr means) were not significantly different with surface-disking tillage versus no surface tillage (4.98 and 4.92 Mg ha^{-1}, respectively). Without subsoiling, corn yields were higher with no surface tillage (4.24 Mg ha^{-1}) than with surface-disking tillage (3.51 Mg ha^{-1}). Likewise, with subsoiling, wheat grain yields (5-yr means) were not significantly different with surface-disking tillage versus no surface tillage (3.12 and 3.24 Mg ha^{-1}, respectively). Without subsoiling, wheat grain yields were higher with no surface tillage (2.80 Mg ha^{-1}) than with surface-disking tillage (2.59 Mg ha^{-1}). Nitrogen accumulations in both shoot dry matter and grain generally followed the treatment responses of grain yield. Thus, during this dry period, surface no-till and the associated accumulation of organic matter could only somewhat compensate for the need to subsoil. With or without surface tillage, paratill subsoiling was very beneficial for corn and wheat yields.

In the southeastern Coastal Plain managing surface residues, eliminating root restriction zones, and utilizing the full growing season via double cropping are important aspects of both crop yield and nitrogen accumulation. Proper management of crop residues and soil organic matter benefits nutrient cycling, water capture, soil physical characteristics, and erosion control (Spivey et al., 1986; Follett et al., 1987; Bruce et al., 1990; West et al., 1991; Hudson, 1994; Endale et al., 2002a, 2002b; Motta et al., 2002; Mosier et al., 2002). Optimizing the management of these important crop residues in the southeastern Coastal Plain was difficult because of the coarse-textured soils and warm, humid conditions of this region, and improvements in soil characteristics and crop yields from residue management were slow (Beale et al., 1955; Blue, 1979). Surface residue management by no-tillage practices was complicated by the general need to subsoil for effective crop production (Campbell et al., 1974; Box and Langdale, 1984). Obtaining the desired advantages of surface residue management with no-till required adaptations for subsoiling (Doty et al., 1975; Busscher et al., 1986; Bruce et al., 1990).

Several in-row, deep tillage tools have been developed to fracture the root restrictive layer in the subsoil while conserving the surface residue (Busscher et al., 1988; Karlen et al., 1996; Hunt et al., 1997). Although the tools varied somewhat in the extent of in-row soil disruption, they were not significantly different in corn yield or the soil strength of the row middles (Busscher et al., 1988). By employing conservation tillage (no surface tillage with in-row subsoiling), which enabled adequate root growth into the subsoil, Hunt et al. (1996) demonstrated it was possible to increase the soil organic matter and nitrogen contents of the surface layer of a Coastal Plain sandy soil with only the return of field crop residues. They were able to double the total carbon in the surface 5-cm layer of a Norfolk loamy sand after 14 yr of continuous use of this conservation tillage system. However, these systems of in-row subsoiling with conservation of surface residue had a problem for narrow row crop production; in-row subsoiling only promoted plant root penetration of the subsoil via a relatively small, disrupted slice through the root-restricting layer under the row.

The problem of undisturbed subsoil in the row middle for double crop, no surface tillage production of winter wheat was successfully addressed with a paratill with shanks set as opposed pairs and spaced 71 cm apart (Frederick and Bauer, 1996). Frederick et al. (1998) also reported significant advantages of no surface tillage and paratill subsoil disruption for drill-planted soybean, which allowed exploitation of the greater subsoil disruption by using narrow rows (19-cm-row spacing). They found the highest wheat and soybean yields using no surface tillage, paratilling, and narrow row spacings. Furthermore, in their system, the advantage of no surface tillage occurred rapidly before the sandy soil had accumulated significantly higher soil organic matter.

Many farmers in the Coastal Plain have been using no surface tillage with wide in-row subsoiling for a num-

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ber of years. It is unknown how combining paratill subsoil disruption with narrow rows affects crop yield on Coastal Plain soils with relatively high organic matter. Because of the improved surface conditions on such soils, we hypothesized that the response might be greater than that found by Frederick and Bauer (1996) and Frederick et al. (1998). We also hypothesized that such a soil with its previously established higher surface organic matter content could better sustain crop yields in a strict no-till system without subsoiling because both organic matter and subsoiling influence soil water, strength, and nutrient availability (Hudson, 1994; Spivey et al., 1986; and Follett et al., 1987; Busscher et al., 1997). The objective of this experiment was to measure the impact of surface and subsoil tillage on grain yield and N accumulation for a 2-yr rotation of corn and wheat–double-cropped soybean grown on a sandy Coastal Plain soil that had been managed with or without surface tillage for 18 yr.

MATERIALS AND METHODS

Design and Experimental Site

This study was conducted on a long-term research site where surface-disked (conventional tillage) and nondisked (conservation tillage) treatments had been compared for 18 continuous years. During this period, the plots had developed very different surface residue and soil organic matter characteristics in the top 100 mm of the soil profile, but the subsoils were similar, having been uniformly managed with in-row subsoiling throughout the previous 18 yr (Karlen et al., 1996; Hunt et al., 1996, 1997). The experimental site was established in 1978 on 2.65 ha of Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Kandiudult) at the Pee Dee Research and Education Center near Florence, SC (34°18′ N, 79°44′ W and elevation is 37 m above sea level). Crops grown during the previous 18 yr included corn, winter wheat, soybean, and cotton (Karlen et al., 1996; Hunt et al., 1997). Weather data were obtained at the site and from the USDA-ARS, Coastal Plain Soil, Water, and Plant Research Center, Florence, SC. The °C growing degree days for each crop's season were calculated by summation of the mean daily minimum and maximum temperatures with limits of 10 and 30°C, respectively: °C growing degree days $= \Sigma[(T_{min} + T_{max})/2) - 10]$, where (i) $T_{min} \geq 10$°C and $T_{max} \leq 30$°C, and (ii) -10 establishes a base line of 10°C.

In this study, we investigated a corn and wheat–double-cropped soybean 2-yr rotation. Both phases of the rotation were performed in two identical sets of plots to allow investigation of each crop in each year. The study was initiated in November of 1997 at the beginning of the wheat–double-cropped soybean rotation. The experimental design was a split plot with five replications. In each year, half of the plots were planted with corn and half with wheat–soybean. Main plots were surface tillage (no-tillage vs. conventional tillage). Conventional tillage consisted of disrupting the soil surface to a depth of 100 to 150 mm with multiple diskings. The subplots comprised different subsurface tillage regimes (no subsoiling vs. paratilling). Paratilling was accomplished with a Tye Para-Till (The Tye Co., Lockney, TX). The ParaTill consisted of four subsoiling-legs (0.66 m apart and 25 mm wide); each was preceded by serrated coulters. The legs were 0.94 m (top to ground) and had a 45° bend (left row to right row and right row to left row) at 0.69 m from the top. Each leg had a 64-mm wide point which was set to a soil depth of 0.42 m. Each leg had a shatter plate above and behind the point to provide gentle lifting and fracturing of soil with minimal disturbance of the surface residue. The appropriate plots were paratilled immediately before the planting of corn, wheat, and soybeans; this resulted in three subsoiling events in the 2-yr cropping rotation. The subplots were 60 m long and 11.4 m wide. This two-by-two factorial design for each crop each year resulted in two rotations with four tillage treatments: (i) neither surface nor subsoil tillage (no-till), (ii) paratill subsoiling without surface tillage, (iii) surface tillage without subsoiling, and (iv) both surface tillage and paratill subsoiling.

Soil cone index was measured in soybean plots 29 July to 3 Aug. 1998, 11 May 1999, 31 July 2000, and 2 Aug. 2001. Dates of measurement were varied because these were generally dry years, and rain was required to soften the soil enough to allow within scale measurements. The penetrometer measured soil strengths up to 7 MPa; cone indices at or above 7 MPa would be well above those considered acceptable for plant root growth in these soils (Busscher et al., 1986). Soil cone index data were taken with a 12.5-mm diameter, 30° solid angle cone tip attached to a hand-operated, recording penetrometer (Carter, 1967). Soil cone indices were measured near the middle of each tillage treatment to a depth of 0.55 m at nine equally spaced positions along a 0.76-m transect of the rows. At each position, measurements were means of three probes that were about 4 cm apart and parallel to the row. Cone indices in the form of analog data were recorded on index cards and subsequently digitized at 5-cm depth intervals. Soil samples were taken randomly across the plots and composited for analyses. They were obtained from the subsoil to a depth of 1 m as well as from the surface-150-mm depth, which was sampled in 50-mm increments. Soil total C and N analyses were performed with a LECO Carbon/Nitrogen Analyzer (Model CN2000; LECO, St. Joseph, MI).

Corn

Each year weeds were controlled by applying cyanazine {2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropanenitrile} and metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide] to the conventional tillage plots at the rate of 1.25 and 2.49 kg a.i. ha^{-1}, respectively, in March. In addition to the conventional tillage herbicides, glyphosate [*N*–(phosphonomethyl)glycine] was applied at the rate of 0.94 kg a.e. ha^{-1} to the no-till plots. In May, glufosinate [2-amino-4-(hydroxymethylphosphinyl) butanoic acid] was applied at the rate of 0.15 kg a.i. ha^{-1}. Granular fertilizer was applied at the rate of 15, 10, and 90 kg ha^{-1}, respectively, for N, P, and K with a 10-ft, 10T series Gandy fertilizer spreader (Gandy Company, 528 Gandrud Rd., Owatonna, MN). Conventional tillage plots were lightly harrowed to incorporate the fertilizer. Corn (cv. Pioneer 34SA55 Liberty Linked) was planted on 31, 30, and 29 March in 1998, 1999, and 2000, respectively, along with 10 Apr. 2001 at a rate of 59 300 seed ha^{-1} with International 800 conservation tillage planters on 0.76-m-row spacing (Table 1). Liquid N (urea ammonium nitrate) was surface applied in May of each year at the rate of 110 kg N ha^{-1}; application was with a Hardy Model MA-200-HC liquid fertilizer sprayer (Hardee Manufacturing Company, Inc., Loris, SC) with spray nozzles on 0.3-m spacing at a height of 0.3 m above the soil surface. An estimate of total corn shoot dry matter was obtained by collecting shoot samples in July; six plants were randomly selected from each plot (Table 1). Shoot dry matter samples (all components) were dried at 70°C, weighed, and ground for N analysis. Grain yield was taken in August or September by harvesting 547 m^2

(12 60-m rows) of each plot with a Case IH Model 2366 combine (Table 1). Subsamples of grain were dried at 70°C and ground for N analysis. Nitrogen content analyses were performed with a LECO Carbon/Nitrogen Analyzer (Model CN2000).

Wheat

Glyphosate was applied at the rate of 0.94 kg a.e. ha^{-1} in October. The conventional tillage plots received multiple diskings. The plots received fertilizer 50, 14, 15, and 1120 kg ha^{-1} of N, P, K, and lime, respectively, in November as previously described for corn. Wheat (cv. Coker 9835) was planted at a seeding rate of 100 kg seed ha^{-1} in November of 1997, 1998, 1999, 2000, and 2001; specific planting dates are in Table 1. Planting was with a no-till grain drill (John Deere Model 750) set on 0.19-m rows. Bromoxynil [oclanoic acid ester of bromoxynil (3,5-dibromo-4-hydroxybenzonitrile)] and ammonium nitrate were broadcast with the previously described Gandy fertilizer spreader in February at the rates of 0.46 kg a.i. ha^{-1} and 91 kg N ha^{-1}, respectively. Wheat shoot dry matter samples were collected in April or May by harvesting 1 m^2 from each plot (Table 1). Shoot dry matter samples were dried at 70°C, weighed, and ground for N analysis. Grain yields were taken in June by harvesting 540 m^2 (9 by 60 m) of each plot with a Case IH Model 2366 combine (Table 1).

Soybean

Following wheat harvest, the no surface tillage plots were sprayed with 0.41 kg a.e. ha^{-1} of glyphosate; the conventional tillage plots were sprayed with 0.45 kg a.i. ha^{-1} of pendimethalin [n-(1-ethylpropyl)-3-4-dimethyl-2,6-dinitrobenzenamine]. Conventional tillage plots received multiple diskings and all plots received fertilizer (10 kg P ha^{-1} and 56 kg K ha^{-1}) before planting as described for corn. Soybean (cv. Northrup King S73Z5) was planted in June of 1998, 1999, 2000, and 2001 at the rate of 112 kg ha^{-1} with the previously described no-till grain drill in 0.19-m rows (Table 1). In July, an over-the-top application of glyphosate (0.41 kg a.e.. ha^{-1}) was applied. Soybean shoot dry matter samples were collected in September or October by harvesting 1 m^2 from each plot (Table 1). Shoot dry matter samples were dried at 70°C, weighed, and ground for N analysis. Grain yield was taken in October or November by harvesting 540 m^2 (9 by 60 m) of each plot with a Case IH Model 2366 combine (Table 1).

Table 1. Tillage, planting, sampling, and harvest dates.

Crop year	Paratill	Planting	Shoot dry matter sampling	Harvest date
		Corn		
1998	Mar. 30	Mar. 31	July 20	Aug. 26
1999	Mar. 24	Mar. 30	July 12	Sept. 8
2000	Mar. 29	Mar. 29	July 27	Aug. 22
2001	April 9	April 10	July 11	Sept. 10
		Wheat		
1997	Nov. 18	Nov. 19	May 14	June 9
1998	Nov. 12	Nov. 12	May 10	June 1
1999	Nov. 1	Nov. 17	May 27	June 1
2000	Nov. 8	Nov. 9	April 27	June 6
2001	Nov. 14	Nov. 16	April 30	June 6
		Soybean		
1998	June 15	June 15	Oct. 2	Oct. 29
1999	June 8	June 18	Sept. 2	Nov. 16
2000	June 20	June 20	–	Nov. 13
2001	June 18	June 20	Sept. 14	Nov. 8

Statistical Analyses

Data were analyzed by analysis of variance (ANOVA) and regression [Statistical Analysis Systems (SAS, 1997)]. Because of significant treatment × year interactions, the data were analyzed and presented separately by year. Additionally, least significant differences (LSD) were calculated for within-year and 5-yr mean comparisons.

RESULTS AND DISCUSSION

Soil

As a result of past and current surface tillage treatments the total soil C and N concentrations means for this study were very different for the surface tillage treatments ($p \leq 0.05$), but the subsoil treatments did not differ significantly ($p > 0.10$). The carbon content of the top 50 mm of soil for surface tilled and no-tilled treatments was 9.4 and 15.5 g kg^{-1}, respectively. The N contents of this layer were 897 and 1539 mg kg^{-1} in the surface tilled and no-tilled treatments, respectively. Whole profile soil strength mean values were lower for the treatment with paraplow subsoiling (Table 2). Though measurements were taken in the soybean treatments, they represent general conditions for the corn and wheat treatments in the similarly treated companion plots adjacent to the soybean plots. Although there were yearly differences, the 4-yr means of soil strength were all above 2 MPa which is considered root limiting (Taylor and Gardner, 1963; Blanchar et al., 1978). This is likely related to the exceptionally dry condition during the experiment as well as the nature of the soil profile (Table 3 and Fig. 1). Thus, the fertility and soil strength data suggest somewhat better soil fertility for the surface no-tillage plots and somewhat better rooting conditions for the subsoiled treatments.

Corn

There were significant ($p \leq 0.01$) positive grain yield responses to both surface no-tillage and subsoil paratilling. There was also a significant surface by paratill interaction ($p \leq 0.10$). Mean grain yields were highest when the subsoil was disrupted by paratilling. For those plots that were subsoiled, there was no significant difference in yields between the continually disked and long-term no surface tillage treatments, 4.92 and 4.98 Mg ha^{-1}, respectively (Table 4). This occurred despite the fact that during the previous 18 yr the nontilled soil surface had accumulated a substantial surface residue

Table 2. Mean soil profile strength as influenced by surface and subsoil tillage.

Tillage: Deep	Tillage: Surface	1998	1999	2000	2001	Mean
		MPa				
Yes	No	3.53	1.88	1.93	2.64	2.50
	Yes	4.37	2.08	2.50	2.61	2.89
No	No	4.06	3.20	3.66	4.46	3.84
	Yes	4.89	3.20	3.38	3.72	3.80
LSD 0.10†		1.2	0.6	1.0	0.8	1.2
LSD 0.05		1.5	0.8	1.3	1.0	1.5

† LSD for comparison of interaction means.

Table 3. Rainfall and temperature data for the growing seasons.

Crop†	Year	Rainfall	$ET_{reference}$	Rainfall − ET	Weeks ET > rainfall	Growing degree days‡
		mm	mm	mm		°C day
Corn	1998	347	633	−286	15	878
	1999	260	573	−313	14	833
	2000	310	590	−280	13	824
	2001	218	572	−354	15	870
	30 yr§	403				
Wheat	1997	821	396	425	6	439
	1998	521	467	54	15	508
	1999	431	467	−36	15	565
	2000	281	437	−156	14	491
	2001	269	411	−142	13	348
	30 yr§	600				
Soybean	1998	229	654	−425	18	1086
	1999	497	605	−108	13	1019
	2000	428	534	−106	14	972
	2001	190	539	−349	18	967
	30 yr§	543				

† Data are for period between planting and maturity; i.e., wheat = 173 d, corn = 120 d and soybean = 139 d.
‡ °C growing degree days = $\Sigma[(T_{min} + T_{max})/2) - 10]$; where (i) $T_{min} \geq 10$°C and $T_{max} \leq 30$°C, and (ii) −10 establishes a base line of 10°C.
§ Southeast Regional Climate Center, 2002.

cover and 67% more organic matter content in the surface 50-mm layer. These grain yield results are generally in agreement with those of Hunt et al. (1996). In that study, all treatments received in-row subsoiling, and corn grain yields were not significantly different between conventional disked or non-disked surface tillage treatments. In the current experiment, it is possible that the lack of positive yield response to the combined effects of no surface tillage and extensive subsoil disruption with the paratill was related to the yield limitations of drier-than-normal conditions during the study period (Table 3). Nevertheless, the results confirm the importance of subsoil disruption to corn grain yield for this sandy Coastal Plain soil.

In the absence of subsoiling, the importance of partially ameliorating plant rooting problems with the higher organic matter and nitrogen contents of no-till is shown. Specifically, without paratilling, the third highest mean corn grain yield, 4.24 Mg ha^{-1}, was obtained with the no-tillage treatment. This is consistent with our hypothesis that long-term no surface tillage and the associated increase in surface organic matter might lessen the need for subsoiling. Although the exact mechanism of amelioration was not determined, higher organic content can lower soil strength via reduced bulk density, increase water holding ability, and increase soil fertility (Spivey et al., 1986; Follett et al., 1987; Hudson, 1994; and Busscher et al., 2001). The lowest corn grain yield, 3.51 Mg ha^{-1}, was obtained in the treatment with surface tillage but without subsoiling. The 1.41 Mg ha^{-1} yield reduction from lack of subsoiling in the surface-disked treatment underlined the necessity for subsoiling in this crop management system that had low organic content and increased subsoil compaction from disking (Busscher et al., 2000).

Corn grain yields were significantly different among the years ($p \leq 0.01$). The lowest yields were obtained in 1998 when they ranged from 2.19 to 3.59 Mg ha^{-1}. These low yields were attributed to adequate rainfall and good shoot dry matter production in the early season followed by drought during the pollination and kernel filling stages (Fig. 1). The best season was 2001 when yields ranged from 4.38 to 6.18 Mg ha^{-1}. The four seasons of this study were very dry relative to other four-

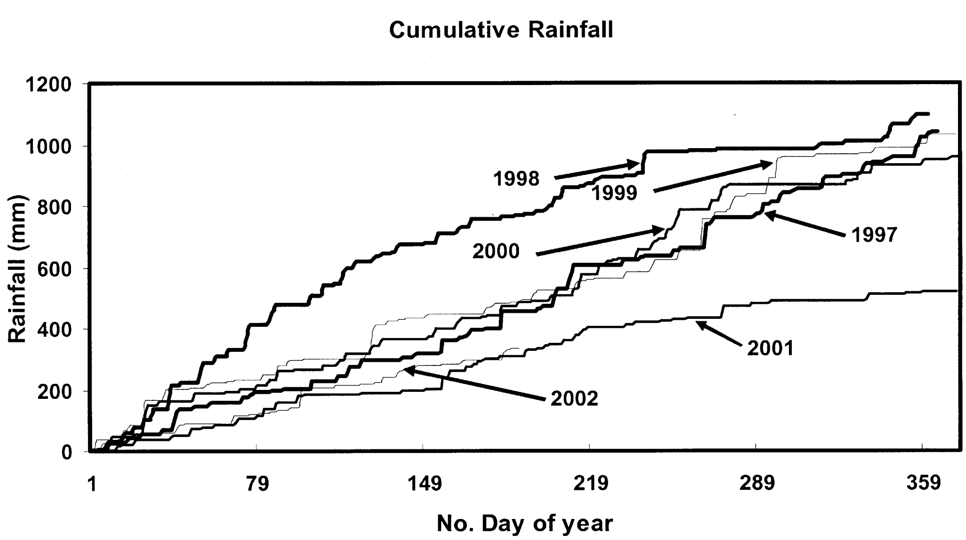

Fig. 1. Rainfall accumulation during the experimental period.

Table 4. Corn grain and shoot dry matter yield as influenced by surface and subsoil tillage.

Tillage		Year				
Deep	Surface	1998	1999	2000	2001	Mean
		Grain Yield (Mg ha^{-1})				
Yes	No	3.52	4.71	5.58	6.18	4.98
	Yes	3.34	5.00	5.80	5.46	4.92
No	No	3.59	3.00	4.90	5.74	4.24
	Yes	2.19	3.53	3.88	4.38	3.51
LSD 0.10†		0.48	0.72	0.49	0.72	0.23
LSD 0.05		0.63	0.94	0.64	0.94	0.30
		Shoot Dry Matter (Mg ha^{-1})				
Yes	No	12.48	7.25	8.76	8.97	9.37
	Yes	11.71	6.78	9.90	10.03	9.61
No	No	10.77	5.16	6.76	6.91	7.40
	Yes	9.49	5.75	6.46	6.71	7.14
LSD 0.10		2.92	1.07	3.12	1.44	0.87
LSD 0.05		3.80	1.39	4.06	1.88	1.13
		Grain/Shoot Dry Matter Ratio‡				
Yes	No	0.28	0.71	0.66	0.70	0.59
	Yes	0.29	0.76	0.62	0.55	0.55
No	No	0.34	0.58	0.76	0.94	0.65
	Yes	0.23	0.65	0.67	0.69	0.56
LSD 0.10		0.09	0.13	0.31	0.21	0.08
LSD 0.05		0.12	0.17	0.40	0.27	0.10

† LSD for comparison of interaction means.
‡ Shoot dry matter was determined on samples taken in July.

Table 5. Corn grain and shoot N as influenced by surface and subsoil tillage.

Tillage		Year				
Deep	Surface	1998	1999	2000	2001	Mean
		Grain N (g kg^{-1})				
Yes	No	13.5	12.9	11.9	13.3	12.9
	Yes	13.9	12.6	13.0	13.5	13.2
No	No	12.8	13.2	12.2	13.4	12.9
	Yes	14.1	12.7	13.1	14.1	13.5
LSD 0.10†		0.6	0.8	0.7	0.2	0.3
LSD 0.05		0.8	1.0	0.9	0.3	0.4
		Grain N (kg ha^{-1})‡				
Yes	No	47	61	67	82	64
	Yes	46	63	75	74	64
No	No	46	39	59	77	55
	Yes	31	45	51	62	47
LSD 0.10		7	12	6	9	3
LSD 0.05		9	16	8	12	4
		Shoot N (kg ha^{-1})§				
Yes	No	119	101	87	99	101
	Yes	120	95	93	112	105
No	No	102	72	64	79	79
	Yes	98	81	78	74	83
LSD 0.10		NS	16	NS	17	11
LSD 0.05		NS	21	NS	22	14

† LSD for comparison of interaction means.
‡ Grain N was determined on samples taken at harvest (August or September).
§ Shoot N was determined on samples taken in July.

year periods (Table 3) during the last 30 yr (Southeast Regional Climate Center, 2002). The 1971 to 2000 mean rainfall accumulation for the corn growing season was 403 mm while the highest rainfall accumulation during this study was 347 mm, and the corn grain yields reflect these drought conditions (Table 3). Nonetheless, the yields and variations were within range of those obtained on this experimental site over the previous 18 yr for both surface disked and nondisked tillage. Over that period, the mean yield for the treatments with no surface tillage and in-row subsoiling was 5.23 Mg ha^{-1} with a range of 1.06 to 8.02 Mg ha^{-1}; similarly, the mean for treatments receiving both surface tilled and in-row subsoiled was 5.30 Mg ha^{-1} with a range of 1.29 to 7.48 Mg ha^{-1}.

There were also significant interactions for both surface tillage by year ($p \leq 0.01$) and subsoiling by year ($p \leq 0.01$). The interaction of surface tillage × year was principally caused by the relatively low corn grain yields of the no-tillage treatment in 1999. In the other 3 yr, the lowest grain yields were for the surface tillage without the subsoiling treatment. The explanation for this variance from the other three years is not clear; the plant stands were similar for tillage treatments (47 685 plants ha^{-1}, standard deviation ± 3223). The rainfall accumulation pattern was similar to that of 2000 (Fig. 1). Moreover, there was relatively little difference among the years for rainfall accumulation, growing degree days, ET, or weeks with ET greater than rainfall (Table 3).

As with grain yield, corn shoot dry matter accumulation was significantly increased by paratill subsoiling ($p \leq 0.01$; Table 4). The mean shoot dry matter accumulations were 9.49 and 7.27 Mg ha^{-1} for the subsoiled and no-subsoil treatments, respectively. However, unlike grain yield, there was not a significant shoot dry matter accumulation difference between the surface tillage treatments ($p \leq 0.82$); moreover, there was no significant interaction of surface tillage and subsoiling treatments ($p \leq 0.45$). Similarly, the interactions of tillage treatments were not significantly different for either surface tillage × year ($p \leq 0.62$) or subsoiling × year ($p \leq 0.73$). The accumulation of shoot dry matter was significantly different for years ($p \leq 0.01$). The greatest shoot dry matter accumulation occurred in 1998, which had a mean of 11.11 Mg ha^{-1} and a range of 9.49 to 12.48 Mg ha^{-1}. The yearly mean for the other 3 yr only ranged from 6.24 to 8.16 Mg ha^{-1} (Table 4).

The ratio of grain to total shoot dry matter was significantly affected by both surface tillage ($p \leq 0.01$) and years ($p \leq 0.01$); the no-surface tillage treatments had higher grain/shoot dry matter ratios (Table 4). However, the partitioning of shoot dry matter was not significantly affected by subsoiling ($p \leq 0.72$), and there was not a significant interaction between surface and subsurface tillage treatments ($p \leq 0.19$). The highest mean grain/shoot dry matter ratio was 0.65 for the no-tillage treatment, while the lowest grain/shoot dry matter ratio was 0.55 for the surface tillage with paratill subsoiling treatment. The difference in partitioning of shoot dry matter may have resulted from better rainfall capture with no-tillage treatment (Bruce et al., 1990). However, an additional factor might be the photobiological effects of differences in light spectra reflected from the clean-tilled soil surface and residue-covered soil surfaces because these differences are known to affect dry matter partitioning (Kasperbauer and Hunt, 1987; Hunt et al., 1989).

Corn grain N concentration was not affected by paratill subsoiling ($p \leq 0.38$), but it was significantly lower for the no surface tillage vs. surface tillage treatments ($p \leq 0.03$), 12.9 vs. 13.4 g N kg^{-1}, respectively (Table 5). Additionally, the N concentrations of corn grain were significantly affected by year ($p \leq 0.02$); yearly means ranged from 12.6 to 13.6 g N kg^{-1}. Despite the differences, treatment trends for N removed in corn grain were generally similar to those for corn grain yield because the magnitude of the N concentration differences was small.

Grain N removal had a significant surface × subsoil tillage treatment interaction ($p \leq 0.05$). When the soil received paratill subsoiling, the corn grain N removal was 64 kg ha^{-1} for both disked and no surface tillage treatments (Table 5). The next highest grain N removal was with the no-till treatment, 55 kg ha^{-1}, and the lowest grain N removal was in the treatment with surface disking without subsoiling, 47 kg ha^{-1}. The N removals in both subsoiled treatments constituted 51% of the 125 kg ha^{-1} of applied N; whereas, only 38% of the applied N was removed by the lowest-yielding treatment, surface tillage without paratill subsoiling. This N could represent a significant potential for denitrification or nonpoint pollution if it was followed by an intensive rainy period (Mosier et al., 2002). In the current experiment, it was most likely part of the N pool available for the production of winter wheat. It should also be noted that the N accumulated by the corn grain was most likely dominated by recycled rather than directly applied N; Karlen et al. (1996) found that only about one-third of a fertilizer N application was removed by corn in a 2-yr rotation.

The N accumulated in shoot dry matter was significantly affected by both year and subsoiling ($p \leq 0.01$), but not by either surface tillage ($p \leq 0.58$) or the surface by subsoil tillage interaction. The season with the highest mean N accumulation (110 kg ha^{-1}) occurred in 1998, when there was abundant early season rainfall; the other years ranged from 81 to 91 kg N ha^{-1} (Table 5). The 4-yr treatment means for N accumulations were 81 and 103 kg ha^{-1}, respectively, for the nonsubsoiled and subsoiled treatments. Much of this accumulated N was removed by the grain, but a fraction would have been returned to the soil. An estimate of the minimum N returned to the soil can be made by assuming that all of the grain N came from the N in the shoot dry matter. In that case, the amounts returned to the soil would range from 24 to 41 kg N ha^{-1} yr^{-1}.

Wheat

Grain yield response to tillage treatments was similar to corn. The 5-yr means for the subsoiled treatments were the highest and not different for the surface tillage vs. no surface tillage treatments, 3.12 and 3.24 Mg ha^{-1}, respectively (Table 6). The third highest mean yield was in the no-till treatment, 2.80 Mg ha^{-1}; and the lowest mean yield was 2.59 Mg ha^{-1} for the treatment with surface tillage without subsoiling.

The yearly mean yields were significantly different ($p \leq 0.01$) ranging from 1.60 to 3.83 Mg ha^{-1} (Table 6), and their differences can be partially attributed to differences in both rainfall and temperature. The lowest yield was in 2001 when there were both low rainfall and low temperatures. Specifically, there was a rainfall to ET deficit of 142 mm, and there were only 348°C growing degree days (Table 3). The best year for wheat yield was 1997, which had 425 mm more rainfall than ET and 439°C growing degree days.

Table 6. Wheat grain and shoot dry matter yield as influenced by surface and subsoil tillage.

Tillage		Year					
Deep	Surface	1997	1998	1999	2000	2001	Mean
		Grain Yield (Mg ha^{-1})					
Yes	No	4.30	2.59	3.27	4.26	1.97	3.24
	Yes	3.86	2.46	3.57	3.95	1.74	3.12
No	No	3.63	2.29	2.96	3.68	1.45	2.80
	Yes	3.63	2.07	2.85	3.13	1.24	2.59
LSD 0.10†		0.41	0.21	0.55	0.37	0.38	0.13
LSD 0.05		0.55	0.27	0.72	0.48	0.49	0.17
		Shoot Dry Matter (Mg ha^{-1})					
Yes	No	9.01	6.79	7.44	11.20	5.14	7.91
	Yes	8.02	7.42	7.28	11.24	4.05	7.60
No	No	8.03	6.14	6.57	7.18	3.85	6.35
	Yes	7.04	5.92	7.08	8.27	3.98	6.46
LSD 0.10		1.11	1.14	0.74	1.91	0.48	0.48
LSD 0.05		1.50	1.48	0.96	2.49	0.63	0.63
		Grain/Shoot Dry Matter Ratio‡					
Yes	No	0.47	0.39	0.44	0.39	0.38	0.41
	Yes	0.48	0.33	0.49	0.36	0.39	0.41
No	No	0.45	0.38	0.45	0.58	0.37	0.45
	Yes	0.52	0.35	0.40	0.37	0.31	0.39
LSD 0.10		0.04	0.06	0.10	0.19	0.08	0.04
LSD 0.05		0.05	0.08	0.13	0.25	0.10	0.05

† LSD for comparison of interaction means.
‡ Shoot dry matter was determined on samples taken in April or May.

The effects of surface and subsurface tillage on shoot dry matter accumulations were similar to those found for grain yields (Table 6). Years were significantly different with shoot dry matter accumulation ranging from 4.26 to 9.47 Mg ha^{-1}. As with grain yield, 2001 had the lowest shoot dry matter accumulation. Paratill subsoiling consistently improved shoot dry matter production; the five-year shoot dry matter accumulation means for the subsoiled and non-subsoiled treatments were 7.76 and 6.41 Mg ha^{-1}, respectively ($p \leq 0.01$). In contrast to paratill subsoiling, tillage of the surface did not greatly affect wheat shoot dry matter accumulation ($p \leq 0.16$), and there was no surface by subsurface treatment interaction ($p \leq 0.64$). The grain/shoot dry matter ratio was not significantly affected by either surface or subsurface tillage. However, years were significantly different ($p \leq 0.01$); values of the 5-yr means of grain/shoot dry matter ratio ranged from 0.39 to 0.45.

Wheat grain N concentration varied considerably with year ($p \leq 0.01$, Table 6). The lowest mean N concentration was 10.0 g N kg^{-1} grain in 1997, which had the highest grain yields. Conversely, the highest mean grain N concentration was 23.3 g N kg^{-1} in 2001, which had the lowest grain yield. There was a moderate inverse relationship between grain yield and N concentration (grain N = −0.40 grain yield + 2.92, $r^2 = 0.54$, $p \leq 0.15$). Whereas the subsoiled treatment had higher yield, it also had lower grain N concentration ($p \leq 0.01$); values were 17.0 and 17.9 g N kg^{-1} grain, respectively, for the subsoiled and nonsubsoiled treatments. Neither surface tillage nor the surface tillage by subsurface tillage interaction was significant for grain N concentration.

Table 7. Wheat grain and shoot N as influenced by surface and subsoil tillage.

Tillage		Year					
Deep	Surface	1997	1998	1999	2000	2001	Mean
		Grain N (g kg^{-1})					
Yes	No	10.0	15.7	21.0	15.8	22.8	17.0
	Yes	9.3	16.8	20.1	15.4	22.9	16.9
No	No	11.0	17.2	21.8	16.0	24.1	18.0
	Yes	10.3	17.6	22.9	15.8	23.5	17.8
LSD 0.10†		NS	1.1	0.9	NS	1.2	0.5
LSD 0.05		NS	1.4	1.2	NS	1.6	0.7
		Grain N (kg ha^{-1})‡					
Yes	No	43	41	68	67	45	53
	Yes	36	41	72	61	40	50
No	No	39	39	64	59	35	47
	Yes	37	36	61	49	29	42
LSD 0.10		NS	5	7	4	9	2
LSD 0.05		NS	7	9	5	12	3
		Shoot N (kg ha^{-1})§					
Yes	No	155	110	117	152	95	126
	Yes	138	123	110	135	89	120
No	No	138	107	123	99	74	108
	Yes	121	106	116	103	80	105
LSD 0.10		19	NS	9	34	11	8
LSD 0.05		26	NS	12	44	14	10

† LSD for comparison of interaction means.
‡ Grain N was determined on samples taken at harvest (June).
§ Shoot N was determined on samples taken in April or May.

Table 8. Soybean grain and shoot dry matter yield as influenced by surface and subsoil tillage.

Tillage		Year of study				
Deep	Surface	1998	1999	2000	2001	Mean
		Grain Yield (Mg ha^{-1})				
Yes	No	1.66	2.45	2.25	0.76	1.78
	Yes	1.75	2.45	2.60	0.68	1.87
No	No	1.70	2.43	2.14	0.83	1.78
	Yes	1.78	2.08	2.51	0.67	1.76
LSD 0.10†		NS	0.20	0.33	0.10	0.10
LSD 0.05		NS	0.26	0.43	0.13	0.13
		Shoot Dry Matter (Mg ha^{-1})				
Yes	No	6.15	4.02	–	3.55	4.57
	Yes	5.81	4.31	–	3.29	4.47
No	No	7.41	4.00	–	3.84	5.08
	Yes	5.70	4.33	–	3.35	4.46
LSD 0.10		0.76	NS	–	NS	0.40
LSD 0.05		0.99	NS	–	NS	0.52
		Grain/Shoot Dry Matter Ratio‡				
Yes	No	0.29	0.63	–	0.22	0.38
	Yes	0.31	0.57	–	0.21	0.36
No	No	0.25	0.62	–	0.22	0.36
	Yes	0.32	0.49	–	0.24	0.36
LSD 0.10		0.08	0.14	–	0.08	0.06
LSD 0.05		0.10	0.18	–	0.10	0.08

† LSD for comparison of interaction means.
‡ Shoot N was determined on samples taken in September or October.

Nitrogen removed in wheat grain differed among years ($p \leq 0.01$); yearly means ranged from 37 to 67 kg ha^{-1}. This would be expected because of the variation in both yield and grain N content over the five seasons. Furthermore, both surface tillage and paratill subsoiling significantly affected grain N removal, $p \leq 0.04$ and 0.01, respectively. The 5-yr means of N removed in the wheat grain ranged from 53 kg ha^{-1} in the no-tillage surface, subsoiled treatment to 42 kg ha^{-1} with surface tillage, nonsubsoiled treatment. There was not a significant surface × subsurface tillage interaction. These removal rates are in agreement with those found by Karlen et al. (1996) using labeled N to compare surface-tilled and no-tilled treatments when both were subsoiled with an in-row parabolic subsoiling tool.

The N accumulated in the wheat shoot varied greatly among years ($p \leq 0.01$); annual means ranged from 84 to 138 kg ha^{-1} (Table 7). Accumulations were greater in the subsoiled treatments than the non-subsoiled treatments, 123 vs. 107 kg ha^{-1} ($p \leq 0.01$). Neither surface tillage nor the surface by subsoil tillage interaction was significant for N accumulated in the wheat shoot. These accumulations of greater than 100 kg ha^{-1} constituted a significant portion of the applied N.

Soybean

Neither surface nor subsurface tillage significantly affected grain yield, and there was not significant interaction among tillage treatments. The lack of response to paratill subsoiling is different from the positive response found by Frederick et al. (1998) and Busscher et al. (2001). The difference between the investigations may have been related to the low rainfall during this investigation because deeper rooting will not give an advantage if the subsoil is depleted of water. Nor will there be an advantage of better rainfall capture if there is little or no rain. These data represent a valuable, albeit unique, documentation of double cropped soybean yield for these tillage systems during the driest 5 yr of the last half century. Negation of tillage response by drought has also been reported by Endale et al. (2002b).

As a result of the substantial variation in yearly rainfall amounts and patterns, soybean yields were significantly different among years ($p \leq 0.01$) ranging from 0.67 to 2.60 Mg ha^{-1} (Table 8). Rainfall accumulations during the growing seasons ranged from 190 to 497 mm (Table 3). Additionally, the seasons were hot; °C growing degree days ranged from 967 to 1086. Because of these conditions ET was significantly greater than rainfall; deficits between rainfall and ET during the soybean growing seasons ranged from 106 to 425 mm. Furthermore, weeks with deficits were common, ranging from 13 to 18 wk.

The lowest soybean yields, 0.67 to 0.83 Mg ha^{-1}, occurred in 2001 when the rainfall accumulation was only 190 mm. The benefit of late season vs. early season rainfall can be seen by the contrast of 1998 against 1999 and 2000 (Table 8; Fig. 1). In 1999 and 2000, rainfall accumulated in the late season, and yields were >2 Mg ha^{-1}. In contrast, the deleterious impact of late season drought can be seen in the yields of 1998 where nearly all of the 229 mm of rainfall occurred by midseason. The ensuing drought and high ET caused a deficit of 425 mm of water, and yields were <1.8 Mg ha^{-1}.

There was also a significant surface tillage × year interaction ($p \leq 0.05$). This was primarily the result of the different yield responses to tillage in 1999 and 2000 (Table 8). The reason for this difference in yield with tillage in these two years is not altogether apparent. There was 69 mm more rainfall in 1999, but the rainfall accumulations in both years were lower than the 30-yr average, 543 mm. In the other years, water stress was so severe that it somewhat masked soybean grain yield responses to tillage treatments.

Soybean shoot dry matter accumulation was not significantly affected by either surface or subsoil tillage, and there was no significant surface × subsoiling interaction. As with grain yield, shoot dry matter was significantly affected by season ($p \leq 0.01$). In 1998 when the early season rainfall was adequate, shoot dry matter accumulations ranged from 5.70 to 7.41 Mg ha^{-1}. In 1999 when early rainfall was limited but late season rainfall was adequate, shoot dry matter accumulations were smaller and very similar for the tillage treatments; they ranged from 4.00 to 4.33 Mg ha^{-1}. In 2001 when rainfall was limited throughout the season, shoot dry matter accumulations ranged from 3.29 to 3.84 Mg ha^{-1}. The seasonal rainfall variation resulted in very different grain/shoot dry matter ratios ($p \leq 0.01$). The highest ratios (0.49–0.63) were in 1999, which had modest shoot dry matter accumulation but the highest grain yields. The lowest ratios, 0.21 to 0.24, were obtained in 2001, a season that had moderate shoot dry matter accumulations but very low grain yields. This was followed by 1998 with ratios of 0.25 to 0.32 because of high shoot dry matter accumulation and moderate grain yields.

These seasonal differences in grain yield and shoot dry matter accumulation also resulted in differences in N accumulation and removal. In the case of 1998, shoot dry matter N accumulation ranged from 168 to 236 kg ha^{-1}, while grain N accumulation ranged from 107 to 113 kg ha^{-1} (Table 9). This resulted in a substantial accumulation of N in the crop residue, and this is quite important to the N cycling within the system. Moreover, a substantial portion of this N was likely added to the crop from dinitrogen fixation (Matheny and Hunt, 1983; Hunt et al., 1985; Hunt and Matheny, 1993). If one assumes that 50% of the shoot N came from fixation during the shoot dry matter accumulation phase (Hunt et al., 1985), there would have been 84 to 118 kg ha^{-1} of N added from dinitrogen fixation. From these data, an estimate of net N accumulation can be obtained [Net N accumulation = N from dinitrogen fixation − N removed in grain]. Thus, we estimated a net of −23 to 5 kg ha^{-1} N in 1998. On the other hand, in 2001, a very dry year, the shoots accumulated only 81 to 104 kg ha^{-1} of N. Dinitrogen fixation of 50% would have produced only 41 to 52 kg ha^{-1} of N. If the N removed in the grain, 37 to 45 kg ha^{-1}, is subtracted from the fixed N, the soil would have received a net of 4 to 7 kg N ha^{-1}. These net N accumulations are much lower than those found in corn of this experiment or in full season determinate soybean in other studies particularly when sufficient water was available (Hunt et al., 1985), and they would not represent a potential for nonpoint pollution from excess N.

Table 9. Soybean grain and shoot N as influenced by surface and subsoil tillage.

Tillage		Year				
Deep	Surface	1998	1999	2000	2001	Mean
		Seed N (g kg^{-1})				
Yes	No	64.3	–	60.9	54.5	59.9
	Yes	63.5	–	60.3	54.2	59.3
No	No	64.2	–	61.0	54.9	60.1
	Yes	63.6	–	61.3	54.0	60.1
LSD 0.10†		NS	–	NS	0.4	0.8
LSD 0.05		NS	–	NS	0.5	1.0
		Grain N (kg ha^{-1})‡				
Yes	No	107	–	137	42	95
	Yes	111	–	157	37	101
No	No	109	–	131	45	95
	Yes	113	–	154	44	108
LSD 0.10		NS	–	NS	6	9
LSD 0.05		NS	–	NS	8	12
		Shoot N (kg ha^{-1})§				
Yes	No	195	115	–	90	133
	Yes	172	116	–	81	123
No	No	236	113	–	104	151
	Yes	168	114	–	85	122
LSD 0.10		35	NS	–	14	15
LSD 0.05		46	NS	–	18	20

† LSD for comparison of interaction means.
‡ Grain N was determined on samples taken at harvest (October or November).
§ Shoot N was determined on samples taken in September or October.

CONCLUSIONS

Results of this experiment provide insight into how these cropping and tillage treatments performed on a sandy Coastal Plain soil during one of the driest 5-yr periods of the last half century. Grain yield responses to tillage were different for the three crops. The four year means for soybean grain yields were low (1.76–1.87 Mg ha^{-1}) and not different for any tillage regime; this result was likely affected by the unusually hot and dry conditions during the soybean growing periods of this experiment. Corn and wheat grain yields were highest for the subsoiled treatments, 4.95 and 3.18 Mg ha^{-1}, respectively; if there was paratill subsoiling, long-term no surface tillage gave no yield advantage. However, without paratill subsoiling, there was a significant grain yield advantage from long-term no surface tillage as compared to surface-disking tillage for corn (4.24 vs. 3.51 Mg ha^{-1}) and wheat (2.80 vs. 2.59 Mg ha^{-1}). Although no-till treatment grain yield was not as large as yields with subsoiling, the potential economic loss from lack of subsoiling would be partially offset by less energy and smaller equipment requirements associated with no-till.

There were some significant effects of surface tillage on the N content of shoot dry matter and grain, but the magnitude of the effects was small. The dominant effect was due to paratill subsoiling. Nitrogen accumulation in the shoot dry matter and grain generally followed the treatment response to grain yield, with the greatest amount being accumulated by the highest yielding treatments. Thus, during this dry period, surface no-till and the associated accumulation of organic matter could only somewhat compensate for the need to subsoil. With or without surface tillage, paratill subsoiling was very beneficial for corn and wheat yield.

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